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Comparison of AIRS, MODIS, CloudSat and CALIPSO cloud top height retrievals

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[1] Knowledge of cloud properties like cloud top height (CTH) is essential to understand their impact on the earth's radiation budget and on climate change. High spectral resolution measurements from the Atmospheric Infrared Sounder (AIRS) are well suited to reveal valuable information about cloud altitude. The CTH retrievals derived from AIRS single field-of-view (FOV) radiance measurements are compared with the operational MODIS (Moderate Resolution Imaging Spectroradiometer) cloud product, and Level 2 products obtained from radar and lidar instruments onboard the EOS (Earth Observing System) CloudSat and the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) satellites. Two cases containing a variety of cloud conditions have been studied, and the strengths/shortcomings of CTH products from infrared (IR) sounder radiances are discussed. **Citation:** Weisz, E., J. Li, W. P. Menzel, A. K. Heidinger, B. H. Kahn, and C.-Y. Liu (2007), Comparison of AIRS, MODIS, CloudSat and CALIPSO cloud top height retrievals, *Geophys. Res. Lett.*, *34*, L17811, doi:10.1029/2007GL030676.

1. Introduction

[2] Clouds play an important role in our environment and climate because they strongly influence incoming solar and outgoing thermal radiation. To accurately describe the energy budget, microphysical properties like cloud phase and particle size and simple geometrical properties like the cloud top height are fundamental. The Atmospheric InfraRed Sounder (AIRS) [*Chahine et al.*, 2006] onboard the Aqua satellite has high-spectral resolution (2378 IR channels in the spectral range from 3.74 μm to 15.4 μm) with a spatial resolution of $\sim$13.5 km at nadir. Sensitivity studies show that AIRS – despite its relatively coarse footprint size – provides sufficient spectral information (from the IR longwave region, in particular) to successfully retrieve cloud properties like cloud top pressure, effective cloud amount, cloud particle size and cloud optical thickness [*Li et al.*, 2005]. The retrieval of cloud top pressure (CTP) from AIRS measurements within the AMSU (Advanced Microwave Sounding Unit) footprint is part of the operational AIRS retrieval product and is described by *Kahn et al.* [2007a]. Studies using high spectral resolution data from the NPOESS (National Polar-orbiting Operational Environmental Satellite System) Airborne Sounder Testbed – Interferometer (NAST-I) confirm the presence of a good signal in the IR region for cloud property retrieval [*Zhou et al.*, 2005, 2007].

[3] Two different methods are used to obtain cloud properties from AIRS and Aqua MODIS. An AIRS research algorithm developed at CIMSS provides sounding profiles (temperature, moisture and ozone) simultaneously with CTP at an AIRS single FOV. The retrieval methodology is based on eigenvector regression and is described in detail by *Weisz et al.* [2007]. The products from this algorithm system are hereafter simply referred to as the AIRS retrieval. MODIS cloud properties (including CTP) are derived from 36 spectral bands in the visible, near infrared and infrared regions at high spatial resolution (1–5 km) [*Ackerman et al.*, 1998; *Strabala et al.*, 1994; *Platnick et al.*, 2003; *Menzel et al.*, 2007]. The method used to retrieve CTP from the MODIS bands is based on the CO_2-slicing technique [*Menzel et al.*, 1983; *Wylie and Menzel*, 1999].

[4] Aqua, CloudSat and CALIPSO are part of the A-train constellation of EOS (Earth Observing System) satellites, which fly in a sun-synchronous orbit at 705 km with a 13:30 PM equator crossing time. Since the satellites fly in close formation to each other (CloudSat and CALIPSO trail Aqua by only 54 and 75 seconds, respectively), measurements from the instruments on the different platforms can be easily compared to each other or merged into combined measurements. This unique multi-satellite observing system is applied in this paper to evaluate AIRS and MODIS CTP retrievals by using radar and lidar measurements.

2. Space-Borne Lidar and Radar Overview

[5] Lidar (light detection and ranging) and radar (radio detection and ranging) can reveal many cloud characteristics by using backscattered electromagnetic radiation. Because these instruments utilize different wavelengths, they have different sensitivities for cloud particles. Lidar operating at optical wavelengths is able to detect thin cirrus, tenuous cloud tops and aerosols, but is attenuated by optically thick clouds. Therefore, space borne lidars can typically provide information on the vertical profile of a cloud through thin cirrus and the tops of opaque clouds. A cloud profiling radar can typically penetrate all non-precipitating clouds but has little sensitivity to thin cirrus especially those cirrus with small particle sizes. In addition, both lidars and radars can provide information on the polarization of the backscattered signals that can be used to deduce the cloud phase and other microphysical properties. Combining information from the

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Table 1. Cloud Top Height Statistics of Instrument Differences

Differences	Number of Pixels	Bias, km	STDE, km
AIRS - CPR	442	−1.1	2.5
MODIS - CPR	1961	−1.2	2.3
AIRS - Caliop	496	−2.8	2.9
MODIS - Caliop	2041	−3.0	3.2
AIRS − MODIS	446	0.1	2.1

lidar and radar allows for a more complete description of the geometrical and microphysical parameters of clouds.

[6] The radar and lidar used in this study are the Cloud Profiling Radar (CPR) on CloudSat and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on CALIPSO. CloudSat is a NASA Earth Sciences Systems Pathfinder (ESSP) mission designed to measure the vertical structure of clouds. The 94 GHz nadir-looking CPR instrument measures the power backscattered by clouds as a function of distance from the radar. CloudSat's 1B CPR standard product (radar backscatter profiles) is combined with auxiliary MODIS and ECMWF (European Center for Medium-Range Weather Forecasts) data to produce the 2B-GEOPROF CPR Cloud Mask product (reprocessing version 3, epoch 1) at 1.1 km horizontal and 240 m vertical resolution that is used for the comparisons shown in section 3. More information about the GEOPROF product can be found in work by *Mace et al.* [2007]. For details on the CloudSat mission, the CPR and its products, the reader is referred to *Stephens et al.* [2002] and to http://cloudsat.atmos.colostate.edu/. The CPR on CloudSat is hereafter referred to as the radar. CALIPSO combines an active lidar instrument with infrared and visible imagers to study the properties of thin clouds and atmospheric aerosols. CALIOP measures the 1064 nm (nanometer) backscatter intensity and the orthogonally polarized components of the 532 nm backscattered signal. The integrated attenuated backscatter is part of the CALIPSO lidar Level 1 data product provided at 30 m horizontal and vertical resolution. This product and the cloud top altitude, which is included in the Level 2 cloud layer data product (version V1-10) produced at 5 km horizontal and 30 m vertical resolution, are used in the comparisons shown in section 3. More information on CALIPSO, its instrumentation and products, can be found at http://www-calipso.larc.nasa.gov/. The term lidar hereafter refers to CALIOP on CALIPSO.

3. Comparison and Evaluation Analysis

[7] Cloud top heights (CTHs) retrieved using the AIRS and MODIS instruments were compared with those obtained using the active sensors onboard CloudSat and CALIPSO. AIRS and MODIS retrieved CTPs were converted to height by using NCEP (National Centers for Environmental Prediction) GDAS (Global Data Assimilation System) analysis profiles of temperature and moisture interpolated to AIRS and MODIS grids. AIRS CTHs are the output from the CIMSS research algorithm, while MODIS CTHs are converted from the collection 5 operational product. It should be noted that NCEP forecast profiles are used in the operational MODIS CTH.

[8] Pixels along the CloudSat/CALIPSO track within seven AIRS granules on July 22, 2006 have been investigated. Table 1 lists the mean difference (bias) and the standard deviation (STDE) of the differences between the cloud top heights obtained using the given instruments. The scenes involve a large variety of cloud types. Only pixels with cloud top heights above 2 kilometers are considered; the highest level of the CloudSat L2 CPR Cloud Mask product with a cloud mask value of at least 30 (indicating high confidence in the cloud detection) is regarded as the CloudSat cloud top.

[9] In general the cloud tops retrieved from AIRS and MODIS agree well. As will be discussed below, these retrievals are closer to the values obtained by CloudSat than the ones obtained by CALIOP. Mean differences of AIRS CTH with respect to CloudSat's CPR and CALIOP are slightly smaller than those associated with the MODIS CTH product.

[10] Two typical cases containing a variety of cloud scenes are presented in detail. The top left image of Figure 1 shows the AIRS brightness temperatures (BT) at wavenumber 911 cm^{-1} for daytime (ascending) granule 8 on July 22, 2006 located off the coast of Antarctica and southeast of New Zealand. The outlines of the co-located MODIS granules are displayed in blue, and the CloudSat/CALIPSO track is shown in black. CTPs retrieved from AIRS and MODIS measurements are displayed in hPa in the left-hand middle and bottom plots of Figure 1, respectively. As seen in the eastern half of the granule (including the region of the CloudSat/CALIPSO overpass), MODIS and AIRS CTP retrievals for high clouds (<400 hPa) are similar, with AIRS CTPs being slightly lower (i.e., higher cloud tops) in some areas. Recent work has shown that the MODIS operational product in collection 4 has difficulties with thin cirrus clouds. *Menzel et al.* [2007] indicate that this has been mitigated somewhat in collection 5. More significant differences between AIRS and MODIS retrievals can be found in areas of low clouds. For $\sim$6600 pixels the mean and STDE of AIRS CTH − MODIS CTH are 1 km and 1.4 km respectively.

[11] The cross-section along the CloudSat/CALIPSO track is shown on the right-hand side of Figure 1. The top image shows CloudSat's L2 CPR Cloud Mask product (i.e., the geometric distribution of the clouds) in gray. Only those cloud mask values $\geq$30, which correspond to cloud detections of high confidence, are displayed. The bottom image shows CALIPSO's 532 nm total attenuated backscatter per km per steradian. The values range from dark (no clouds) to white (strong backscatter from clouds). Overlaid on both panels are the cloud tops in kilometers obtained from AIRS (red circles) and MODIS (green circles) measurements as well as the first layer top altitude provided by CALIOP (blue dots).

[12] According to CloudSat's Level 2 cloud classification (2B-CLDCLASS) product (not shown), most of these clouds are nimbostratus, with some altostratus (e.g., north of latitude $-55°$) and cirrus. The latter can be found in the upper parts of the two-layer regions around latitude $-66°$ and latitude $-58°$.

[13] The right-hand side of Figure 1 also illustrates the difference between the lidar and radar instruments in characterizing clouds. Lidar is very sensitive to optically thin clouds, and therefore detects higher cloud top altitudes (e.g., between latitudes $-58°$ and $-68°$) but due to its short

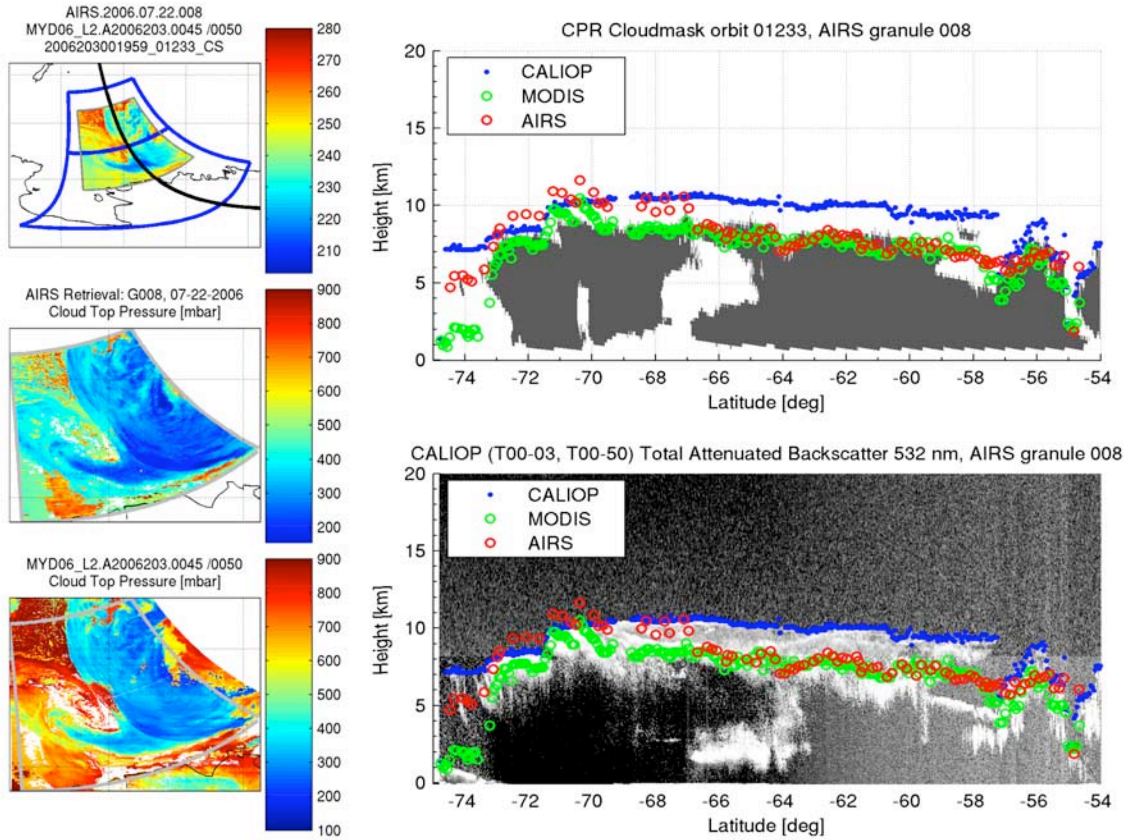

Figure 1. (left) BT in Kelvin for (top) AIRS granule 8 on July 22, 2006, with outlines of MODIS granules (blue), and CloudSat/CALIPSO track (black); (middle) AIRS retrieved CTP; and (bottom) operational MODIS CTP (MYD06) product. (top right) CPR cloudmask and (bottom right) CALIOP 532 nm total attenuated backscatter /km/steradian. The cloud top altitudes from AIRS, MODIS and CALIOP are plotted as red circles, green circles and blue dots, respectively.

wavelength cannot detect the thick cloud structure underneath (e.g., between latitudes −68° and −73°). In contrast, radar penetrates thick clouds underneath thinner clouds (e.g., between latitudes −68° and −73°), and is able to measure their extent but is not able to detect thin clouds at higher levels and therefore underestimates the cloud tops (e.g., between latitudes −58° and −68°). Together they provide a better description of cloud distribution and extent.

[14] Optically thick clouds have greater IR sensitivity (i.e., larger differences between cloudy and clear radiances) for CTP than transparent clouds. Thus, for thick clouds AIRS and MODIS CTH values are close to those values obtained by the radar and lidar for the areas between latitudes −54° and −57° (except the narrow region around latitude −56°), and from latitudes −71° to −72°. In the area between (i.e., from latitudes −57° to −71°) the lidar retrieves higher altitudes of cirrus clouds, which the radar does not observe. Overall, MODIS CTPs mirror the radar's CTPs very closely. Results from AIRS are similar although in some areas AIRS CTH attempts to follow the higher altitudes as seen by the lidar (e.g., from latitudes −67° to −69°).

[15] These differences (and the ones around latitude −56°) between AIRS and the lidar cloud tops are expected to be reduced when an iterative physical inversion algorithm is applied [*Li et al.*, 2000]; this step will account for the non-linearity between observed radiances and retrieval parameters.

[16] The AIRS and MODIS algorithms have difficulties retrieving correct CTPs in the two-layer region around latitude −58°; values between the layers are obtained. Including two cloud layers in the retrieval algorithm should yield better results, although proper handling of 2-layer clouds in the IR is challenging.

[17] Discrepancies between AIRS and MODIS retrievals arise from different instrument characteristics (high spectral resolution versus high spatial resolution); the AIRS retrieval is able to capture small vertical features (e.g., at latitude −74°), whereas the MODIS retrieval can reproduce horizontal features of high variability (e.g., from latitudes −57° to −55°). In addition, different retrieval methodologies are employed. The AIRS retrieval system is based on an eigenvector regression scheme using all good AIRS spectral channels; the operational MODIS algorithm utilizes the CO_2-slicing technique to derive the CTP or an 11 μm window channel method [*Platnick et al.*, 2003; *Menzel et al.*, 2007]. Radiances from the 15 μm CO_2 absorption band region are better suited to detect transmissive clouds like cirrus than IR window channels. Due to the fact that the CloudSat cloud mask algorithm uses the MODIS (MOD35) cloud mask product (see section 2), the correlation between the two products needs to be considered as well.

[18] The conversion of cloud heights in pressure (hPa) to height in kilometers introduces a further error that needs to be considered when comparing AIRS/MODIS retrievals to lidar and radar products.

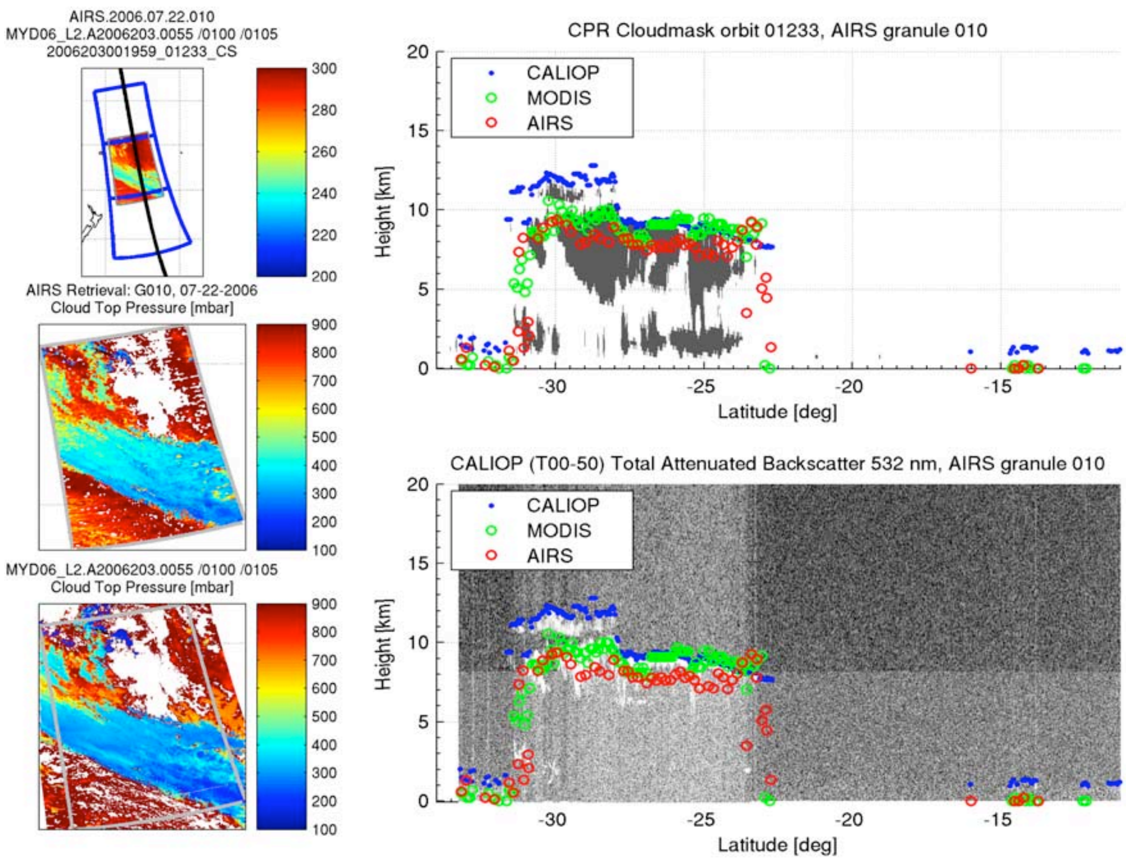

Figure 2. (left) BT in Kelvin for (top) AIRS granule 10 on July 22, 2006, with outlines of MODIS granules (blue), and CloudSat/CALIPSO track (black); (middle) AIRS retrieved CTP and (bottom) operational MODIS CTP (MYD06) product. (top right) CPR cloudmask and (bottom right) CALIOP 532 nm total attenuated backscatter /km/steradian. The cloud top altitudes from AIRS, MODIS and CALIOP are plotted as red circles, green circles and blue dots, respectively.

[19] These issues also apply to the next case, which describes a frontal system northeast of New Zealand. The top left image of Figure 2 shows AIRS BT at wavenumber 911 cm^{-1} for daytime granule 10 on July 22, 2006 together with the outlines of the MODIS granules and the CloudSat/CALIPSO track. According to the AIRS and MODIS retrieved CTP (left middle and bottom images), this case includes clear regions, clouds with high cloud tops and also large areas of very low clouds.

[20] The CTP inferred from AIRS measurements compares well with the MODIS operational product with a bias of -1.1 km and a standard deviation of 1.5 km for $\sim$4400 pixels. The current case also includes some two-layer structures, which can be seen in the right-hand side of Figure 2 displaying the CPR Cloud Mask, the CloudSat attenuated backscatter and the retrieved AIRS, MODIS and the CALIOP cloud top altitudes.

[21] The 2B-CLDCLASS product of CloudSat (not shown) assigns altostratus (north of latitude $-29°$) and cirrus (south of latitude $-29°$) to the clouds with a base above 4 kilometers, and stratocumulus for most of the clouds below that height. In areas of cirrus clouds, AIRS and MODIS retrieval products disagree more significantly with CALIPSO while they are closer in agreement for altostratus clouds. This finding is consistent with the tenuous nature of cirrus and the tendency of IR-derived CTP to be placed well within the cirrus cloud [*Holz et al.*, 2006], whereas altostratus is more opaque and the CTPs are expected to be in better agreement.

[22] Cloud altitudes ranging between 8 and 10 km are found by radar and lidar between latitudes $-24°$ and $-28°$. MODIS retrieved CTP compares very well to those. The AIRS retrieval algorithm finds somewhat lower values. Again, an iterative physical inversion method will be able to reduce this type of discrepancy [*Li et al.*, 2000]. It is also noticeable that lidar is not able to penetrate the base of these clouds, and cannot detect the shallow clouds near the surface.

[23] The scene south of this region (i.e., latitudes $-28°$ to $-31°$) consists of an optically thinner cloud layer (with lidar cloud tops $\sim$12 km) above an optically thick cloud. The cloud top of the latter (lidar cloud tops from the second layer and beyond are not plotted in the figure) is measured by the lidar to be $\sim$10 km. Both AIRS and MODIS retrievals place the cloud top near the radiance mean of the two cloud layers. Regarding lower clouds (e.g., stratocumulus) AIRS is able to detect the cloud occurring around latitude $-31°$. Cloud tops of very low clouds (e.g., south of $-31°$) are difficult to retrieve due to low IR sensitivities for CTP below 700 hPa.

[24] Studies of other cloud scenes (not shown here, but included in the statistics of Table 1) show that the CTP from AIRS measurements generally agrees well with the operational MODIS CTP product and the CTP from the active

sensors, but AIRS has difficulties with broken clouds with small horizontal extent due to its large footprint size. On the other hand its high spectral resolution enables the detection of small vertical variations. This ability is confirmed by case studies performed over Antarctica where strong temperature variations near the surface are often present. For example in the case of AIRS granule 39 on July 22, 2006 (not shown here), the AIRS research algorithm is able to retrieve reasonable cloud heights, which are favorably evaluated by CloudSat along the entire track. MODIS gives much lower values with its infrared window estimates.

4. Summary

[25] Using comprehensive information on cloud distribution obtained from active instruments onboard the CloudSat and CALIPSO satellites, cloud top pressure retrievals from AIRS and MODIS measurements can be properly evaluated.

[26] Two case studies involving clouds of various types, thicknesses, and vertical and horizontal extents have been presented. Mean statistics show that in general reasonable cloud top altitudes are obtained from AIRS and MODIS radiances. Inconsistencies between AIRS and MODIS products originate in part from retrieval algorithm differences, and in part from instrument differences. Due to the nature of infrared measurements, the ability to retrieve altitudes of optically thin cirrus clouds and very low clouds is limited, although AIRS is better suited to retrieve thin cirrus than MODIS (see also *Kahn et al.* [2007b]). In addition, the relatively coarse spatial resolution of AIRS prevents an accurate CTP retrieval in broken clouds with small horizontal extent. While AIRS and MODIS see effective cloud top and have similar CTH performance for most cloud conditions, they have distinct differences with regard to low clouds. AIRS has an advantage in CTP retrieval over polar regions, where low level temperature inversions (which heavily impact the CTP accuracy) can be detected by AIRS; in contrast, MODIS restricts CTP retrieval to above the inversion due to the limited information from its spectral bands and the NCEP forecast model. The independent evaluation of CTP using space-borne active sensors is ongoing and includes many other case studies. These studies (and validation with radiosondes and dropsondes) are supporting algorithm development designed to fully utilize AIRS and MODIS measurements. Current work includes improving the cloudy transfer model and the cloudy training set for the AIRS CTP retrieval. Since an AIRS footprint often contains multi-layer clouds, including at least two-layer clouds in the algorithm, like that implemented in the AIRS operational retrieval algorithm [*Kahn et al.*, 2007a], is an important task to improve the overall retrieval outcome. Since the cloudy radiance is a non-linear function of the atmospheric and cloud parameters, an iterative physical inversion method is necessary to further improve the results. The physical algorithm from the AIRS longwave channels will provide retrievals of cloud optical thickness and cloud particle size as well. Synergistic use of AIRS and MODIS (e.g., described in a variational retrieval by *Li et al.* [2004]) is expected to provide better CTP retrievals than from using either one alone.

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